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Remote Solar, Wind, and Hybrid Solar/Wind Energy Systems for Purifying Water

Solar energy, wind energy, and a combination of wind and solar energy have been used successfully to power an UV (ultraviolet) water purification system. Five different solar and wind energy systems have been tested and although these renewable energy systems have been used for water purification, graphs contained in the paper can be used to determine the feasibility of powering other electrical loads. Combining a 100-W solar-PV system with a 500-W wind turbine resulted in pumping and purifying enough water to satisfy the potable water requirements of 4000 people (16000 liters/day) at an estimated equipment cost of $4630. [DOI: 10.1115/1.1531148]

Introduction

Drinking unsafe water is a major problem in the world. "In developing countries, 80% of all diseases are caused by consuming water contaminated with pathogens and pollution. One in five people in the world do not have clean drinking water. Providing safe drinking water and improving sanitation could reduce the suffering from water related diseases" [1]. Several ways of disinfecting water using solar energy have been designed and tested [2,3]. Most of these systems are simple to construct but don't purify enough water for an entire village. One thermal device was developed which purified water for about 625 people at an equipment cost of $1680 [4]. Some companies have manufactured units, which purify water with ultraviolet (UV) light and use solar energy as the power source. An UV water purification unit was tested at the USDA-ARS (United States Department of Agriculture–Agricultural Research Service) Conservation and Production Research Laboratory in Bushland, Texas. This unit was shown to meet the World Health Organization's standards for disinfecting water by several health agencies [5]. However, the only way to power the unit was by utility supplied electricity and most of the people in the world in need of disinfecting unsafe water also did not have access to electrical power from a large power plant. A partner of the company which manufactured the UV water purification unit contracted with the West Texas A&M University-Alternative Energy Institute (WTAMU-AEI) to design a controller which would enable the UV water purification unit to be powered by solar and wind energy systems. WTAMU-AEI designed the UV and dump load controllers that enabled solar and wind energy devices to power the UV water purification unit via a deep cycle battery. Testing and further development of the renewable energy powered UV water purification unit was performed at the USDA-ARS Laboratory in Bushland, Texas.

Previous testing had shown that the water purification unit could purify water if the flow rate did not exceed 15.1 L/min (4 gal/min) and the UV light intensity did not drop below 10% of its rated value. This previous testing was also done with an overhead storage tank and used gravity to cause the water to flow through the unit. There were two problems with using gravity to cause the water to flow through the unit and they were:

1. How to stop the flow of water through the unit if the UV light intensity was low
2. Sizing with a full storage tank so that the water would not exceed the maximum flow rate

Since the maximum flow rate would occur with a full storage tank, the flow rate would constantly decrease as the water in the storage tank decreased. It was decided by the design and testing team at WTAMU-AEI and USDA-ARS that instead of using a large tank for gravity flow into the water purification UV unit, an inexpensive bilge pump and flow meter would be used. Using a bilge pump and a flow meter enabled a controller to change the amount of electricity going to the pump motor if the selected flow rate varied from the measured flow rate or in the case of a 10% low UV light intensity—completely shut off the pump motor with the controller. This configuration change (bilge pump and flow meter instead of an overhead storage tank) also resulted in an increase in performance since the flow rate would not decrease. If the water was coming from a lake or stream, then the water could be pumped directly without using any kind of a storage container for the dirty water. Since previous testing showed the water was safe to drink coming out of the unit (assuming the water was similar to that in [5]) if the flow rate did not exceed 15.1 L/min and the UV light intensity didn't drop below 10% of its rated value, testing the water quality coming out of the unit was felt to be unnecessary.

UV and Dump Load Controllers. The UV controller used an inexpensive microcontroller chip to operate the UV system efficiently and reliably. This controller maintained constant water flow rate and UV light intensity although the battery voltage varied from 11.5 to 15 V and the charging current from the wind and/or solar energy systems was fluctuating significantly. The battery lifetime can be several years if it is not discharged below about 80% of the fully charged capacity, and that it is not overcharged more than 10%. The low cut-off voltage for the controller was 11.5 V, which for a new battery will be at 30% of the fully charged capacity if this battery voltage is reached (an older battery may be close to fully discharged at this voltage). However, since the wind and/or solar system will be continually charging the battery during the discharging, the 11.5 V cut-off should seldom

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be reached. In the beginning of the testing, the controller kept the batteries from being overcharged by only charging the batteries when the system was turned on. It was determined later that a dump load to absorb the excess renewable energy would increase the amount of water that could be purified and protect the batteries from overcharging. An electrical dump load can contain resistive and/or capacitive elements and its purpose is to absorb surplus electrical power. The controller dump load consisted only of a resistive element capable of dissipating 1 kW of power generated by a small wind and/or solar system. Using a dump load also kept the wind turbine from spinning too fast because the wind turbine was always loaded. Reduced rotor speed also reduced the noise and extended the lifetime of the wind turbine. The UV controller monitored and displayed the following parameters:

1. Input voltage
2. Battery voltage
3. Flow rate
4. UV light intensity
5. Load current for UV light
6. Load current for the pump motor
7. Remaining pump time

An 8-bit switch was used to set the flow rate and running time. Four bits were used for the flow rate setting (0.5–7.5 gal/min with 0.5-gal/min increments) and four bits were used for running time setting (0.5–7.5 hr with 0.5-hr increments). The system can run 24 hr if the running time setting is zero. The system starts and keeps running whenever you push the start/stop key and remains running until one of the following occur:

1. Setting time is reached
2. Battery voltage is below 11.5 Volts
3. UV light intensity is below 90% of maximum
4. Collection tank is full
5. Source tank is dry or pipe is blocked
6. Start/stop button is pushed again

After almost 2 years of testing with renewable energy systems ranging from 100 W to 600 W, few modifications have had to be made. The only changes made have been to increase the power rating and the amount of cooling surface of the MOSFET chips in the dump load controller.

Data Instrumentation and Acquisition

A schematic of the UV water purification and data acquisition systems is shown in Fig. 1. The data collected were: Julian day, time of day, wind speed (m/s), solar irradiance (W/m^2), load current (A), battery voltage (V), charging current (A), UV light intensity (V), and flow rate (gal/min).

The wind speed was measured with a cup anemometer, which was 1 m below the hub height (hub height = 10 m) of the 300-W wind turbine. The anemometer was mounted on a bar located 1.5 m from the centerline of a tower, which was also the tower the 300 W wind turbine was mounted on. This wind turbine (1.17-m rotor diameter) was rated at 300 W at a wind speed of 12.5 m/s. The tower and wind turbine were located on the southwest corner of the Renewable Energy Laboratory Building–the prevailing wind was from the southwest. The 500-W wind turbine was mounted on a tower located about 26 m west of the Renewable Energy Laboratory Building, and this wind turbine (1.52 m rotor diameter) was rated at 500 W at a wind speed of 12.5 m/s. The wind speed for this wind turbine was measured with another cup anemometer on a tower located 30 m west of the wind turbine tower. The hub height for this wind turbine was 14 m and the anemometer height was at 15.2 m.

The solar irradiance was measured with a pyranometer and was mounted on the upper end of the solar panel frame holding the solar panels. The two polycrystalline silicon solar panels used were rated at 50 W per panel. They were located on the south end of the Renewable Energy Laboratory Building and set approximately to the latitude of Bushland, 36 deg. The solar panels were always fixed at approximately 35 deg during the testing, but since a linear relationship of charging current to average daily energy could be determined, different fixed panel angles and tracking systems could be evaluated.

The load current was measured with an ammeter, and the charging current was measured by determining the voltage drop across two resistors. The output from an UV light sensor was connected to the datalogger and the UV controller. The flow rate was measured with a magnetic paddle wheel flow meter, which was calibrated to be within 0.5 L/min. The batteries used were deep cycle marine/RV batteries rated at 120 Amp-hr each (6A for 20 hr). Four different bilge pumps were used during the testing; they were rated from 2839 to 5678 L/hr (750–1500 gal/hr). The bilge pump

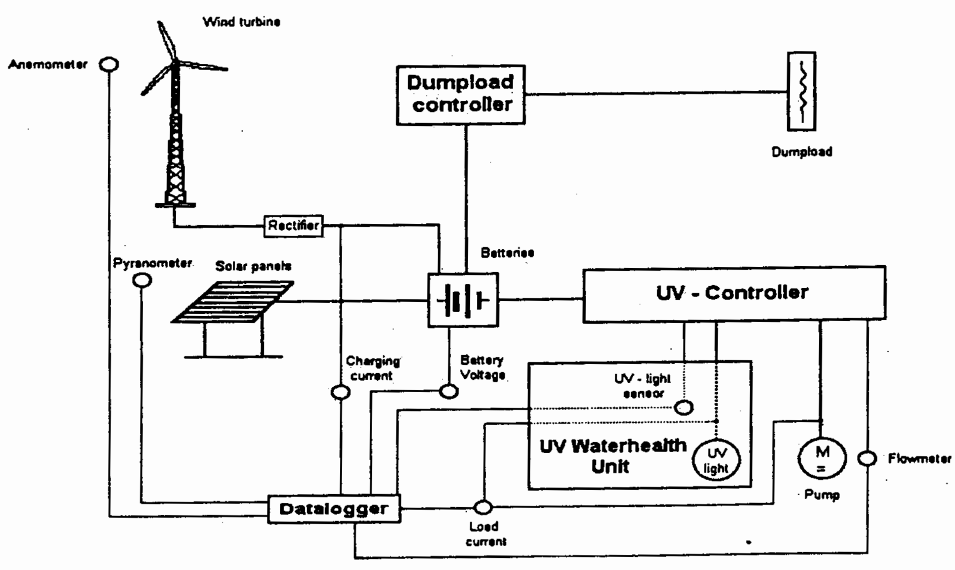

Fig. 1 Schematic of UV water purification system

appears to be the number one maintenance item in this system in that it had to be replaced every 3–12 months depending on how many hours/day the system was pumping.

The data acquisition system was a datalogger, which could store up to 9 analog and 4 pulse input signals. The analog inputs (solar irradiance, load current, battery voltage, charging current, and UV light intensity) were sampled every second. The pulse inputs (wind speed and flow rate) were sampled every 10 s. The 5-min averages of the measured data were stored in a storage module. The data from the storage module were downloaded to a computer usually twice a week and imported into a spreadsheet where the data were checked.

Results

Figures 2 and 3 show an example of the data collected on the UV water purification system. At about 8:00, the system was turned on. One can tell the system is on by the sudden increase in the load current and water flow rate. One should also notice that the charging current begins at the same time there is an increase in solar irradiance—at about 7:15. If one is running either a solar or wind system and the battery voltage is low, then it would be better to wait until later in the morning to turn the system on. This is due to the fact that both wind and solar energy typically increase later in the morning. At about 10:30, the charging current is greater than the load current, so the battery voltage begins increasing. At about 13:30, the spikes in the wind speed match the spikes in the charging current, so the wind turbine is beginning to affect the charging current. At 15:30, the flow rate and load current go to zero which implies that the time limit was set to 7.5 hr. At about 16:10, the system is again turned on by the operator and stays on another 7.5 hr when the system shuts itself off again just before midnight. In order to get 15 hr of operating time, the system has to be turned on after the first 7.5 hr is finished due to the limitation of timer settings (0.5–7.5 hr or 24 hr) on the controller. The UV light intensity and the flow rate remain relatively constant even though the battery voltage is changing significantly which indicates the importance of the controller.

Usually when data is binned or graphed for solar energy systems, the independent variable is solar irradiance (W/m^2). For wind energy systems, the independent variable is usually wind speed (m/s). However, to graph both wind and solar systems together, the independent variable has to be the same. We decided to use daily insolation (kWhr/m^2) as the independent variable. This is also a common independent variable to use for solar systems, but not for wind systems. The equation for the power in the wind from Gipe [6] is:

$$P=\tfrac{1}{2}\rho_{\mathrm{air}}V^3S_{\mathrm{ref}} \tag{1}$$

where

$$P=\text{wind power (W)}$$

$$\rho_{\mathrm{air}}=\text{air density (kg/m}^3\text{)}$$

$$V=\text{wind velocity (m/s)}$$

$$S_{\mathrm{ref}}=\text{swept area of wind turbine rotor (m}^2\text{)}$$

Since power is the time rate of change of energy, then an equation for energy is:

$$E=P\Delta t \tag{2}$$

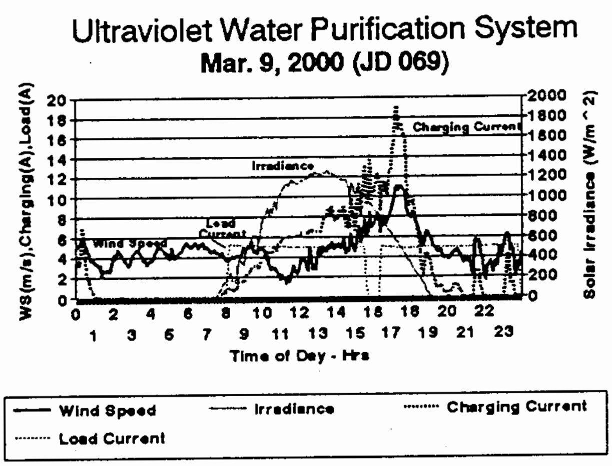

Fig. 2 Example of data collected on UV water purification system

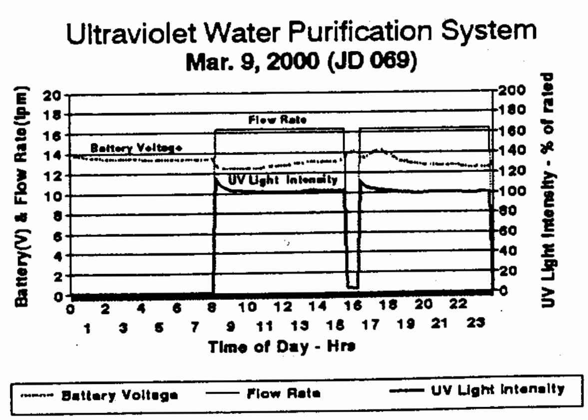

Fig. 3 UV light intensity and flow rate remain constant despite changing battery voltage

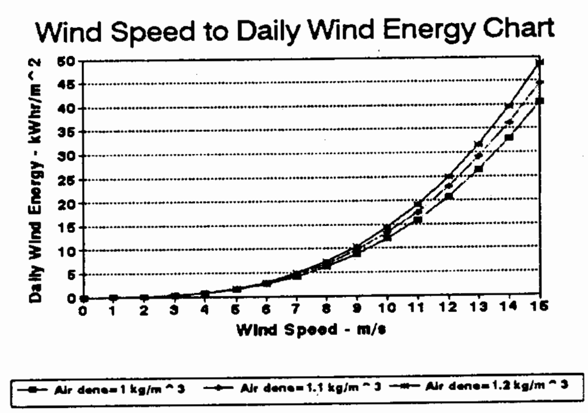

Fig. 4 Conversion of wind speed to daily wind energy

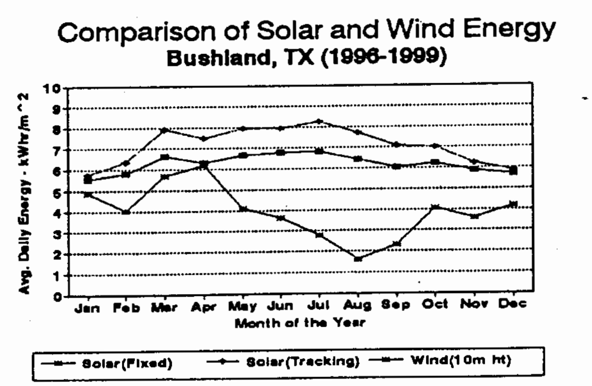

Fig. 5 Measured average solar and wind energy at Bushland, Texas

where

$$E = \text{wind energy (W hr)}$$

$$\Delta t = \text{some interval in time (hr)}$$

Substituting Eq. (1) into Eq. (2) gives the following equation:

$$E = \tfrac{1}{2}\rho_{air}V^3 S_{ref}\Delta t \tag{3}$$

Dividing Eq. (3) by the swept area of the wind turbine rotor and using a time interval of 24 hr gives:

$$E/A = \tfrac{1}{2}\rho_{air}V^3(24\ \text{hr})\ (\text{kW}/1000\ \text{W}) \tag{4}$$

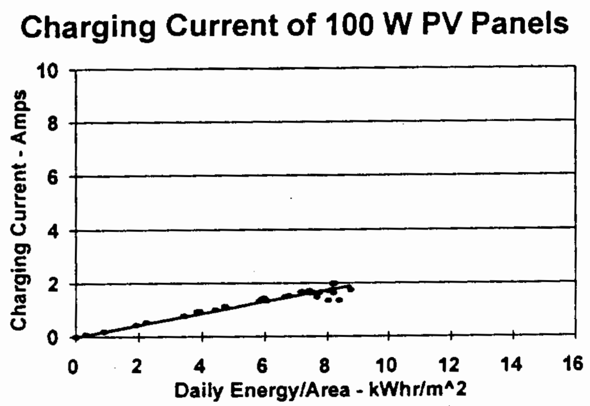

Fig. 6 Measured charging current of 100-Watt solar PV system

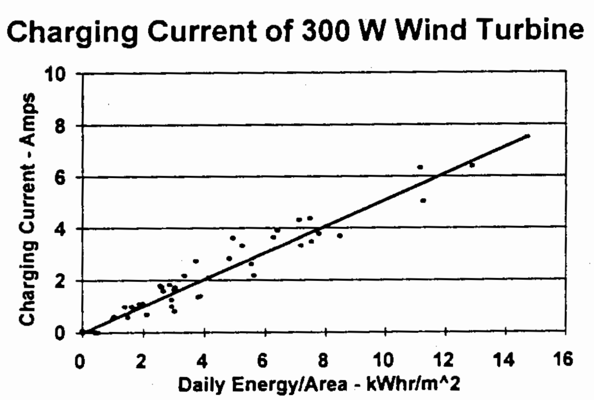

Fig. 7 Measured charging current of 300-Watt wind turbine

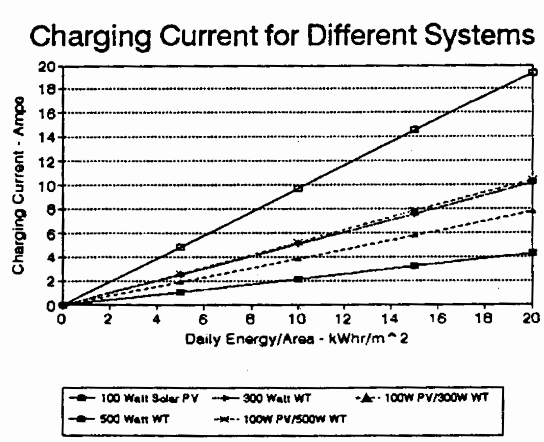

Fig. 8 Linear approximation of measured charging current for all renewable energy systems tested

E/A is the Daily Wind Energy per unit area and the units for Eq. (4) will be kWhr/m^2. Figure 4 is a graphical representation of Eq. (4) for various values of air density (the air density in Bushland usually varies between 1 and 1.2 kg/m^3). The air density was obtained from another data acquisition system when the daily wind energy was determined. Figure 5 shows a comparison of the daily average wind and solar energy for the years 1996–1999 measured at Bushland, Texas. Both fixed and passive tracking data have been measured at Bushland. The wind data was measured at a 10-m height from a data acquisition system that has been collecting wind data since the spring of 1982. The solar data was obtained from another data acquisition system that has been collected since the winter of 1995. During all four years, the solar panel angle for both fixed and tracking systems was changed at the equinoxes to always stay within 12.5 deg of the optimum panel angle [7]. Further information on the passive tracking system can be found in [8,9]. The result in Fig. 5 was surprising in that we always felt there was more energy in the wind than in the incident solar radiation, but that is obviously untrue. If the solar devices were more efficient than the wind devices in converting the energy into usable work, there might be more solar farms than wind farms. Of course the wind energy will increase significantly as the height is increased, and will likely be better than solar at a 50-m height due the cubic relationship of wind velocity to power in the wind. Another thing to notice in this figure is that the solar energy for Bushland is much more constant from month to month than the wind energy. This would imply that for Bushland the water pumped each month by the solar unit would be more constant than the wind unit.

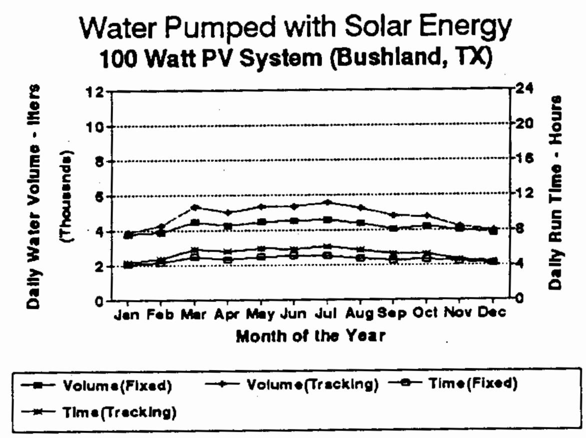

Fig. 9 Predicted daily water volume and run time of 100-Watt PV system with fixed and tracking panels

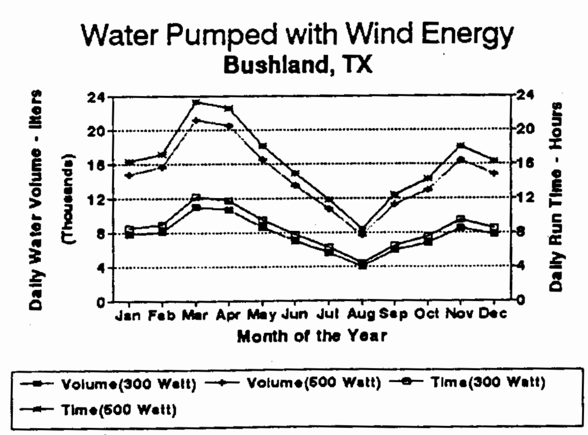

Fig. 10 Predicted daily water volume and run time of wind energy systems

The charging current data for the 100-W PV system are shown in Fig. 6. The charging current varies depending on the battery voltage and the panel efficiency and results in the data scatter. A least squares fit line is also drawn through the data. Figure 7 shows the charging current data for the 300 W wind turbine. Again there is scatter in the data due to changing battery voltage and a least squares fit line is drawn through the data. Figure 8 shows the least squares fit lines through the charging current data for all the systems tested. Although it would appear the hybrid wind/solar systems are worse than the wind systems alone, one should not forget that the daily energy for the wind/solar systems is higher than the wind only systems.

Using the charging current trend curves in Fig. 8 with the daily energy data in Fig. 5, the average daily run time and water pumped can be estimated for each of the renewable energy systems for Bushland, Texas. Four more assumptions were also made in order to make daily water volume and run time predictions, and they were:

1. the load amps would be 6 A
2. the flow rate would be 15.1 L/min (4 gal/min)
3. there would be enough batteries to absorb all the charging amps
4. the water purified would not be dirtier than that tested in references listed in [5]

Assumption 1 was fairly typical for all the bilge pumps tested when the flow was around 15.1 L/min and the UV light intensity was about 100% of the rated. Assumption 3 may not be valid for wind systems in high winds because there may not be enough batteries to absorb the charging current. If Assumption 4 is wrong, that could mean more water can be purified (water is cleaner than that tested) or in some cases, none of the water can be purified because it is too dirty. The parts and estimated costs of the renewable water purification system were:

1. UV water purification unit - $1500
2. Deep cycle 12-V wet cell battery (120 amp-hours) - $85
3. 100-W solar-PV fixed system (passive tracking) - $640 ($1100)
4. 300-W or 500-W wind turbine with rectifier and tower - $1000 - $1800
5. Estimated UV and dump load controllers - $200
6. 12-V DC bilge pump motor - $50
7. Flow meter and UV light sensor - $100

Figure 9 shows the predicted water volume and run time for the 100-W solar-PV system with fixed and passive tracking panels. Since one person in a developing country needs about 4 L of potable water per day, the fixed panel system should be able to purify enough water to satisfy the water requirements of 1000 people at an initial equipment cost of $2575 (1 battery). Figure 10 shows the predicted daily water volume and run time of the 300-W and 500-W wind turbines. The water volume and run time for the 500-W wind turbine is approximately twice that of the 300-W wind turbine. The yearly average water volume of the 300-W wind turbine is twice the yearly average water volume of the 100-W solar-PV system. In addition, if it was desirable to pump a certain quantity of water each month, then the 300-W wind turbine would be equivalent to the 100-W solar-PV system, and the 500-W wind turbine would only be twice that of the 100-W solar-PV system. Figure 11 shows the daily water volume and runtime of the hybrid wind/solar systems. Combining the 100-W solar-PV fixed panel system with the 300-W wind turbine gives a system which can purify enough potable water for 3000 people in a developing country at an initial equipment cost of $3660 (2 batteries). The 500-W wind turbine combined with the 100-W solar-PV fixed panel system results in enough potable water for 4000 people in a developing country at an initial equipment cost of $4630 (4 batteries). During the higher wind energy spring months, this hybrid would be able to run 24 hr/day. Again, it should be emphasized that enough batteries would need to be available to absorb all the charging current at these higher wind speeds.

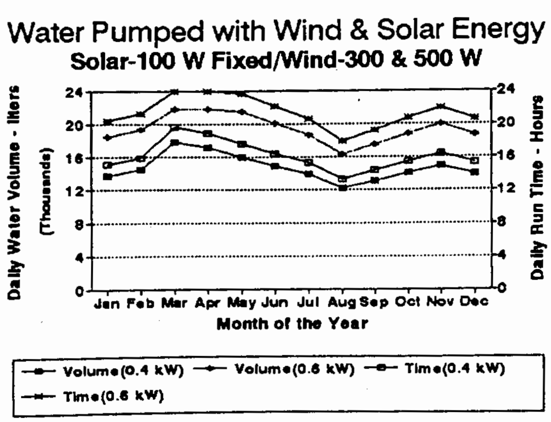

Fig. 11 Predicted daily water volume and run-time of hybrid wind/solar systems tested

Conclusions

The UV and dump load controllers designed for using wind and solar energy to purify water have operated reliably for almost two years. The solar only system appears to be more efficient and cost effective than the wind only system for a solar and wind resource similar to that of Bushland, Texas. However, combining the wind and the solar system together would be more reliable than either one alone. The cost of the systems should be affordable for developing countries since the initial equipment cost ranges from $1.15 to $2.60 per person. Additional costs like replacement bilge pumps, batteries, UV light bulb, controller chips, wind system parts, and solar system parts are hard to estimate because of the difference between laboratory test conditions and real world field conditions. The next step would be to install some of these systems in developing countries to determine how reliable they really are. Because thousands of people are dying each year due to drinking unsafe water, this phase of testing should occur soon.

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